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The Transmission of Stress to Grafted Bone Inside a Titanium Mesh Cage Used in Anterior Column Reconstruction After Total Spondylectomy: A Finite-Element Analysis

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Study Design. A finite-element study of posterior alone or anterior/posterior combined instrumentation following total spondylectomy and replacement with a titanium mesh cage used as an anterior strut.

Objectives. To compare the effect of posterior instrumentation *versus* anterior/posterior instrumentation on transmission of the stress to grafted bone inside a titanium mesh cage following total spondylectomy.

Summary of Background Data. The most recent reconstruction techniques following total spondylectomy for malignant spinal tumor include a titanium mesh cage filled with autologous bone as an anterior strut. The need for additional anterior instrumentation with posterior pedicle screws and rods is controversial. Transmission of the mechanical stress to grafted bone inside a titanium mesh cage is important for fusion and remodeling. To our knowledge, there are no published reports comparing the load-sharing properties of the different reconstruction methods following total spondylectomy.

Methods. A 3-dimensional finite-element model of the reconstructed spine (T10–L4) following total spondylectomy at T12 was constructed. A Harms titanium mesh cage (DePuy Spine, Raynham, MA) was positioned as an anterior replacement, and 3 types of the reconstruction methods were compared: (1) multilevel posterior instrumentation (MPI) (*i.e.,* posterior pedicle screws and rods at T10–L2 without anterior instrumentation); (2) MPI with anterior instrumentation (MPAI) (*i.e.,* MPAI [Kaneda SR; DePuy Spine] at T11–L1); and (3) short posterior and anterior instrumentation (SPAI) (*i.e.,* posterior pedicle screws and rods with anterior instrumentation at T11–L1). The mechanical energy stress distribution exerted inside the titanium mesh cage was evaluated and compared by finite-element analysis for the 3 different reconstruction methods. Simulated forces were applied to give axial compression, flexion, extension, and lateral bending.

Results. In flexion mode, the energy stress distribution in MPI was higher than 3.0×10^{-5} MPa in 73.0% of the total volume inside the titanium mesh cage, while 38.0% in MPAI, and 43.3% in SPAI. In axial compression and extension modes, there were no remarkable differences for each reconstruction method. In left-bending mode, there was little stress energy in the cancellous bone inside the titanium mesh cage in MPAI and SPAI.

Conclusions. This experiment shows that from the viewpoint of stress shielding, the reconstruction method, using additional anterior instrumentation with posterior pedicle screws (MPAI and SPAI), stress shields the cancellous bone inside the titanium mesh cage to a higher degree than does the system using posterior pedicle screw fixation alone (MPI). Thus, a reconstruction method with no anterior fixation should be better at allowing stress for remodeling of the bone graft inside the titanium mesh cage.

Key words: spondylectomy, titanium mesh cage, finite-element method, stress-shielding, spinal instrumentation, spinal fusion, bone remodeling. **Spine 2005;30: 2783–2787**

Palliative surgery, such as curettage and intralesional resection, has been the common clinical practice for spinal malignant tumors. However, this surgery has had high rates of local recurrence[1–3] in patients with long-term survival. Recently, to achieve radical resection oncologically, aggressive surgery has been advocated. Tomita *et al*[4,5] described an innovative surgical technique, termed "total en bloc spondylectomy," using a T-saw for malignant tumors or aggressive benign tumors of the thoracic and lumbar spines. Total en bloc spondylectomy is indicated for patients with malignant spinal bone tumors, who are expected to survive long term.[6] Also included are those patients with metastasis or aggressive benign tumors. The development of this procedure provided the patients with spinal malignant tumor long-term local control.[4–8] Therefore, long-term maintenance of spinal stability is required in reconstruction following this procedure. On the other hand, from the biomechanical point of view, total en bloc spondylectomy presents a complete loss of spinal stability because the vertebral bone and surrounding ligaments are resected totally to excise the tumor mass, including a wide or marginal margin. Thus,

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postoperative reconstruction is an important part of this surgery.

A titanium mesh cage can provide structural support.[9] With the expectation of attaining fusion, morcellized autograft can be used inside the cage before insertion. The cage is positioned as an anterior strut, and pedicle screws are inserted in the 2 levels above and 2 levels below the location of the spondylectomy.[4,5,10] In contrast, there are reports about another reconstruction method, whereby anterior instrumentation, such as Kaneda SR system (DePuy Spine, Raynham, MA), is added to the pedicle screw instrumentation.[11,12]

It has been well defined that mechanical stress is necessary for bone remodeling.[13–27] Therefore, transmission of stress to the grafted bone inside the titanium mesh cage would be important for fusion and remodeling. Rigid fixation could eliminate the transmission of stress, thus a construct that allows adequate stress to pass through the bone in the cage is preferable. To investigate this procedure, we performed a finite-element analysis to compare the effect of 3 reconstruction methods on the stress transfer through the grafted bone inside a titanium mesh cage used as an anterior column reconstruction following total spondylectomy.

■ Materials and Methods

Reconstruction Groups

The thoracolumbar spine (T10–L2) was harvested from a formalized human cadaver spine from a 90-year-old male with no spinal diseases. Total spondylectomy was performed at T12, and a Harms titanium mesh cage (25-mm diameter × 40-mm high; DePuy Spine) was positioned as an anterior strut. There were 3 methods of instrumented reconstruction (Figure 1). All spinal instrumentation systems were made of titanium.

Multilevel Posterior Instrumentation (MPI). There were 2 pedicle screws (Moss-Miami system; DePuy Spine) inserted in both sides of T10, T11, L1, and L2 pedicles (Figure 1A). There were 6.0-mm diameter polyaxial pedicle screws, 40-mm in length, used at T10 and T11, and 45-mm in length at L1 and L2. Two 5.5-mm diameter rods were attached to the pedicle screws, and 2 posterior cross-link transverse connectors were used between T11 and L1. A compressor was used to apply the compressive force between T11 and L1 on the titanium mesh cage when tightening the rod-screw junctions.

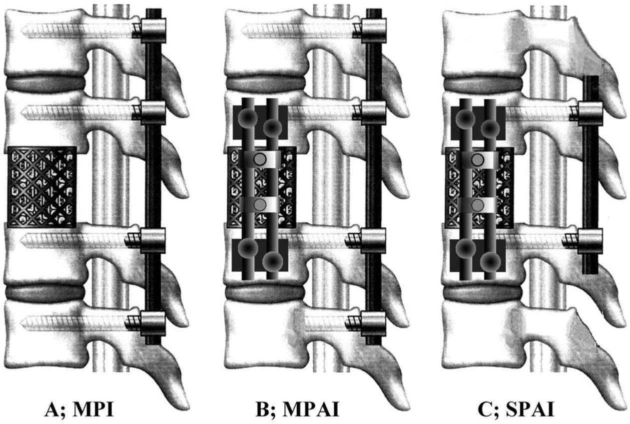

Figure 1. Three types of instrumented reconstruction method following total spondylectomy. **A**, MPI. **B**, MPAI. **C**, SPAI.

MPI with Anterior Instrumentation (MPAI). The Kaneda SR system (4, 6.25-mm diameter vertebral body screws penetrating the opposite surface and 2, 6.35-mm diameter rods, with 1 caudal and 1 rostral plate) was applied in addition to the MPI between T11 and L1 (Figure 1B). There were 2 transverse rod couplers applied.

Short Posterior and Anterior Instrumentation (SPAI). The rod-pedicle screw junctions at both sides of T10 and L2 were removed, and the pedicle screws inserted at T10 and L2 were removed from MPAI (Figure 1C). This meant that posterior pedicle screws and rods were applied only between T11 and L1.

Finite-Element Models

Three-dimensional finite-element models of the reconstructed structure were developed from computerized tomography data taken from reconstructed spines of the cadaver specimen. The reconstructed spine consisted of cortical bone, cancellous bone, intervertebral disc, cartilage of the facet joints, titanium mesh cage, grafted bone in the titanium mesh cage, posterior instrumentation, and anterior instrumentation. The material of each was assumed to be isotropic and homogeneous, and the material constants of cortical bone, cancellous bone, intervertebral disc, cartilage of the facet joint, anterior and posterior longitudinal ligament, supraspinous ligament, interspinous ligament, ligamentum flavum, capsular ligament, and intertransverse ligament are summarized in Table 1.[28,29] No loosening condition was considered at the interfaces between bone and the instrumentation. The material constant of the bone inside the titanium mesh cage was considered cancellous bone because cancellous morcellized bone is usually packed inside the titanium mesh cage in the clinical situation. The model consisted of 11,646 elements and 14,033 nodes.

Finite-Element Analysis

The mechanical stress exerted on the cancellous bone inside the titanium mesh cage was evaluated by finite-element analysis for the 3 different reconstruction methods (MPI, MPAI, and SPAI) under axial compression, flexion, extension, and lateral-bending loading modes. MSC. Marc (MSC. Software Co., Tokyo, Japan) was used for the stress analysis.

Axial Compression

The bottom of the L2 body was fixed, and an arbitrary compressive force of 424.7 N (approximately the weight of the

Table 1. The Material Properties Used in the Finite-Element Model

Material	Young Modulus (MPa)	Poisson Ratio
Cortical bone	12,000	0.30
Cancellous bone	100	0.20
Grafted bone	100	0.20
Instrumentation	110,000	0.30
Titanium mesh cage	35,000	0.30
Disc	7.5	0.40
Cartilage	0.6	0.49
Ligaments (ALL, PLL)	20	0.40
Ligaments (SSL, ISL, LF, CL, ITL)	10	0.30

ALL indicates anterior longitudinal ligament; CL, capsular ligament; ISL, interspinous ligament; ITL, intertransverse ligament; LF, ligamentum flavum; PLL, posterior longitudinal ligament; SSL, supraspinous ligament.

upper body in an adult[30]) was applied to the axis of the top of T10 body to analyze under the axial compression loading mode.

Flexion, Extension, and Lateral Bending

The loading plate was fixed on the top of T10 in all models. This process acted to receive the compressive force and never moved or changed its shape. The flexion-loading mode was made as: a 424.7-N load was applied at 3-cm anterior to the axis of the top of T10, which produced a flexion moment of 12.7 Nm (*i.e.*, 0.03 × 424.7 = 12.7 Nm). Extension, right bending, and left-bending loading mode were made using the same method as the flexion-loading mode. In other words, a 424.7-N load was applied 3-cm posterior to the axis of the top of T10 for extension mode, 3-cm right for the right-bending mode, and 3-cm left for the left-bending mode.

■ Results

The energy stress distributions in the cancellous bone packed inside the titanium mesh cage in flexion, right lateral bending, and left-lateral bending mode are shown in Figure 2. The energy stress distribution in MPI was symmetrical, while the stress distribution in MPAI and SPAI was not symmetrical in axial compression, flexion (Figure 2A), and extension modes.

In flexion mode, the energy stress distribution in MPI was higher than 1.0×10^{-5} MPa in 98.9% of the total volume inside the titanium mesh cage, while 89.0% in MPAI, and 78.2% in SPAI. The percentage volume that was higher than 3.0×10^{-5} MPa was 73.0% in MPI, 38.0% in MPAI, and 43.3% in SPAI (those are shown as reddish in color in Figure 2A). The percentage volume that was higher than 5.0×10^{-5} MPa was 25.1% in MPI, 11.1% in MPAI, and 24.6% in SPAI. The percentage volume that was higher than 1.0×10^{-4} MPa was 4.7% in MPI, 2.2% in MPAI, and 5.6% in SPAI. In both axial compression and extension modes, there was little difference in energy stress distribution between each reconstruction method.

In right-bending mode, there were no remarkable differences between MPI and MPAI (Figure 2B). While in the left-bending mode, there was a high variation in the energy stress distribution (Figure 2C). In left-bending mode, there was little energy stress applied to most of the

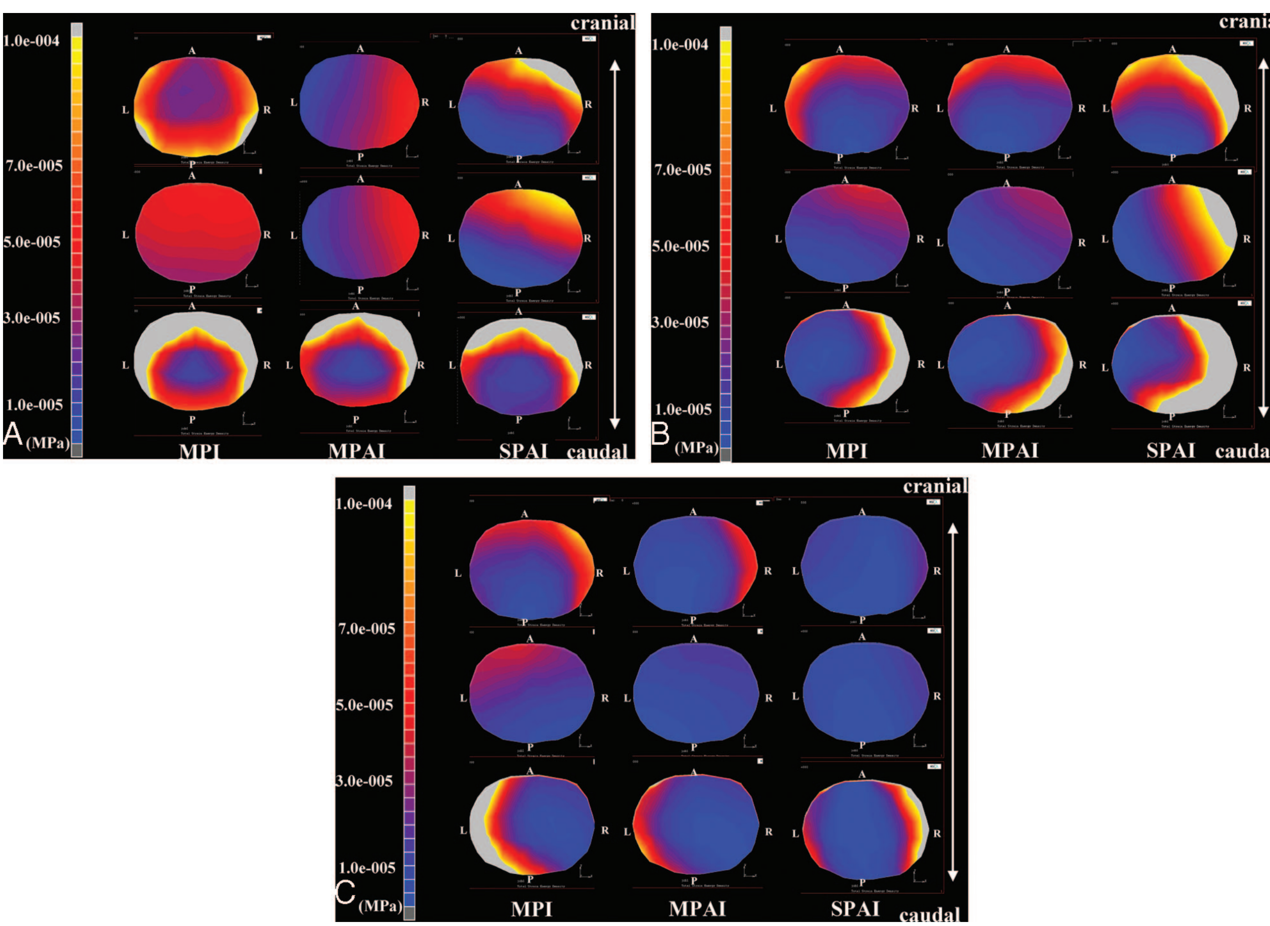

Figure 2. Representative axial tomographic views of the energy stress distribution (MPa) of the grafted cancellous bone inside the titanium mesh cage in each loading mode. **A**, Flexion. **B**, Right-lateral bending. **C**, Left-lateral bending. The upper, middle, and lower panels in each column are representative axial tomographic views just under the caudal endplate of the T11, middle of the cage, and just upper the cranial endplate of the L1, respectively. The 3 columns represent views at MPI, MPAI, and SPAI, moving from left to right. The upper-side of the each panel indicates anterior (A) direction, lower indicates posterior direction (P), right indicates right direction (R), and left indicates left direction (L). The color scale represents stress magnitude. The bluish color indicates that less energy stress could be seen, and the reddish color shows more energy stress could be seen inside the mesh cage from 1.0×10^{-5} MPa to 1.0×10^{-4} MPa.

cancellous bone inside the titanium mesh cage in MPAI and SPAI (this area is shown as bluish in color in Figure 2C). On the other hand, energy stress was seen in the right side inside the titanium cage in MPI (this area is shown as reddish in color in Figure 2C). In MPI, the images of right-bending mode and left-bending mode were symmetric (Figures 2B, C).

Discussion

The development of total en bloc spondylectomy has given patients with spinal malignant tumor some long-term local control.[4–8] On the other hand, total en bloc spondylectomy presents a complete loss of spinal stability, therefore, primary stable reconstruction followed by biologic bony fusion is an important part of this surgery. There are advantages to using titanium mesh cages in corpectomy: varying diameters and heights are available, they can provide high resistance to subsidence,[9] and they can maintain spinal alignment without collapse. Furthermore, with the expectation of attaining fusion, the titanium mesh cages can be filled with morcellized autograft before insertion.

To achieve grafted bone union, rigid immobilization of the grafts is required.[27] However, adequate stress must be transmitted to the grafts during the reparative period to stimulate the repair as well. The balance between the 2 is the most important concept for spinal fixation, which means the stable fixation system that allows adequate stress transmission for grafted bone is necessary for union and remodeling of the grafted bone.

There are only a few studies on the biomechanical properties of the reconstruction method following total spondylectomy.[10–12] Oda *et al*[12] made reconstruction models after total spondylectomy of L2 using human cadaver spines and tested the stiffness biomechanically. They concluded that the 4 pedicle screws (L1–L3) with the Kaneda SR systems (L1–L3) (SPAI) or the 8 pedicle screws (T12–L4) with the Kaneda SR systems (L1–L3) (MPAI) were significantly stiffer than the 8 pedicle screws (T12–L4) alone (MPI). They also stated that MPI was stiffer than the intact spine in flexion, extension, and lateral bending tests, and was not significantly different from the intact under axial compression. Although Ikebuchi[10] investigated the stiffness of the MPI using finite-element analysis and concluded that this reconstruction method had enough stability for primary fixation, the reconstruction section might have failed because of fatigue; therefore, biologic bony fusion was required for the long-term maintenance of stability. These former studies indicated that each of the 3 methods (MPI, MPAI, and SPAI) had enough stability for primary reconstruction following total spondylectomy.

On the other hand, there is evidence to suggest that eliminating mechanical loads on healing bone when using rigid fixation may result in negative bone remodeling and net bone loss. Thus, less rigid fixation that permits a certain degree of micromotion may accelerate the time to union.[13–27] Therefore, transmission of the mechanical stress to the grafted cancellous bone inside the titanium mesh cage is important for fusion and remodeling. The environment of the grafted bone inside the titanium cage must be protected from mechanical stress because of the high structural support of the titanium mesh cage.[9]

The current experiment showed that from the viewpoint of stress shielding, the reconstruction method using additional anterior instrumentation with posterior pedicle screws (MPAI and SPAI) stress shielded inside the titanium mesh cage to a higher degree than did the system using posterior pedicle screw fixation alone (MPI). Thus, the reconstruction method with MPI alone would allow more stress to reach the grafted bone inside the titanium mesh cage and should be a better method of reconstruction following total spondylectomy. There are some clinical reports documenting fusion status using structural titanium mesh cages. Those studies indicated the advantages of multilevel posterior pedicle screw fixation alone. Akamaru *et al*[31] reported that the grafted bone inside the titanium mesh cage was not absorbed, and bony fusion with adjacent vertebral bodies was achieved within 1 year in the reconstruction method with MPI alone following total spondylectomy. Akamaru *et al*[32] also showed a case to confirm histologic remodeling and fusion of the grafted bone inside the titanium mesh cage with the adjacent vertebral bodies with the MPI alone following total spondylectomy using the postmortem specimen.

The mechanical stresses on the posterior rods at the upper and lower levels of the spondylectomy would be higher in MPI and MPAI because these levels were not fused, and a certain degree of micromotion would exist in an anterior column of the spine. This effect is a disadvantage of multilevel segmental long fixation, and there is the risk of instrumentation breakage in the long term. This disadvantage was detected in the study by Ikebuchi.[10] The authors believe that the removal of the posterior rods and screws is preferable after the grafted bone inside the titanium mesh cage remodels and fusion occurs, if long-term survival is expected.

Total spondylectomy can be performed with the single-posterior approach using the T-saw technique. MPI with an anterior titanium mesh cage can also be performed with a single-posterior approach, although the additional transcavitary approach is needed for anterior instrumentation. The authors do not believe that additional anterior instrumentation is needed in the reconstruction following total spondylectomy.

Conclusions

This experiment shows that from the viewpoint of stress shielding, the reconstruction method using additional anterior instrumentation with posterior pedicle screws (MPAI and SPAI) stress shields the cancellous bone inside the titanium mesh cage to a higher degree than does the system using posterior pedicle screw fixation alone (MPI). Thus, a reconstruction method with no anterior fixation should be better at allowing stress for remodeling of the bone graft inside the titanium mesh cage.

■ Key Points

- A finite-element analysis of 3 different types of reconstruction following total spondylectomy was performed, and the mechanical stress on the cancellous bone inside the titanium mesh cage used as an anterior strut was measured and compared.
- The 3 methods of reconstruction were multilevel posterior instrumentation (MPI), multilevel posterior instrumentation with anterior instrumentation (MPAI), and short posterior and anterior instrumentation (SPAI).
- From the viewpoint of stress-shielding, the reconstruction method using additional anterior instrumentation with posterior pedicle screws (MPAI and SPAI) stress-shields the cancellous bone inside the titanium mesh cage to a higher degree than does the system using posterior pedicle screw fixation alone (MPI).

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